Proton Radiography

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Introduction

Los Alamos National Laboratory is leading a multilaboratory effort to demonstrate protons as a viable new radiographic probe to image imploding or exploding objects with high spatial and temporal resolution. Proton radiography represents a sharp departure from flash x-ray radiography techniques, which have been used to image dynamic processes for over 40 years. In the past, protons were used for imaging only thin objects, but the technique was limited because the proton's charge caused multiple scattering of the proton in the object, leading to a blurred image. However, we have recently demonstrated a magnetic lens system that removes the majority of the blur—even for thick objects. This technique can be extended to gain information on the material composition of an object in addition to its density by cascading two lenses with different angular apertures—a feature that conventional x-ray radiography cannot match.

An advanced radiographic capability is an essential component of the Laboratory's Science-Based Stockpile Stewardship (SBSS) program because it provides the ability to measure the integral performance of stockpiled primaries using inert materials and thereby derive nuclear performance information that previously could be obtained only from nuclear testing. Detailed data from hydrodynamic experiments are the necessary starting points for modeling the explosion phase of the primary and thus for assessing the performance and safety of stockpiled primaries.

In the interest of expanding our hydrotest capabilities to include experimental validation of calculated nuclear performance, the Advanced Hydrotest Facility (AHF) has been proposed (Fig. 1). The AHF will provide improved understanding of three-dimensional (3-D) effects associated with aging and weapons features, as well as time-dependent, high-resolution measurements of pit density and gas-cavity configurations. The AHF will require an advanced radiographic capability that provides accurate information about densities and material positions, from which we can infer the degree of supercriticality, the shape of the boost cavity, and the mix that would be present in an actual imploding primary. Allowed manufacturing tolerances can cause an implosion to be 3-D (deviating from two-dimensional symmetry) even in normal operation, and accidental detonations are almost always 3-D. As a result, radiographs are needed from a number of directions (at least four and preferably 12) so that material densities can be reconstructed with accuracies sufficient to derive nuclear parameters. Also, since the implosion progresses with time, a temporal series of radiographs (5–10) is needed over a time period relevant to the processes being recorded. This time window may need to cover a period as long as the full implosion.

Currently, two radiography options are being considered for the AHF, one using multi-GeV protons and one using multi-MeV x-rays. Ultimately, the results for both options will be compared to determine an optimal technology mix for the AHF. Because an actual hydrotest at 50 GeV was not feasible at existing high-energy accelerator facilities, the Tri-Laboratory External Advisory Committee for Advanced Hydrotesting Research, which oversees AHF development, deemed that a combination of dynamic experiments at the Los Alamos Neutron Science Center (LANSCE) using 800-MeV protons and a suitable static demonstration at 25 GeV at Brookhaven National Laboratory's Alternating-Gradient Synchrotron (AGS) would provide enough data to evaluate proton radiography as a viable candidate for the AHF.

In collaboration with scientists, engineers, and technicians from Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, Indiana University, and Bechtel Nevada, we have been collecting the data necessary to make that assessment. This research highlight provides an overview of proton radiography and a summary of the work that has been (or will be) done at LANSCE and the AGS.

Overview of Proton Radiography

Hydrodynamic radiography refers to a technology used to view inside thick material objects (specifically the primaries of nuclear weapon assemblies) as they are undergoing implosion and compression because of the detonation of surrounding high

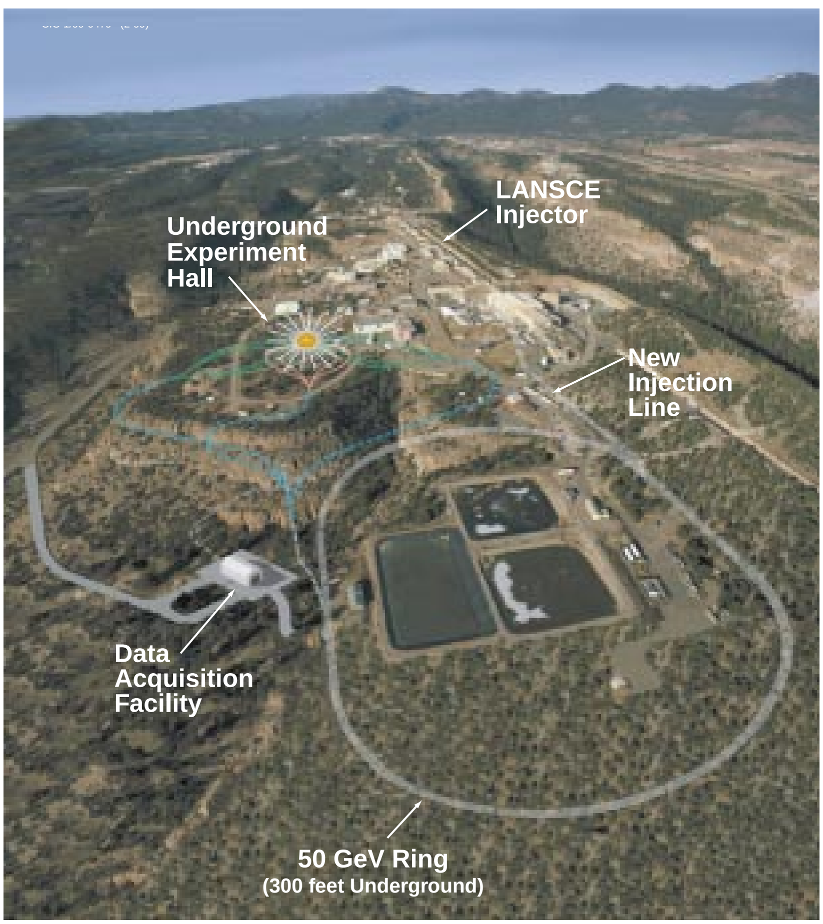


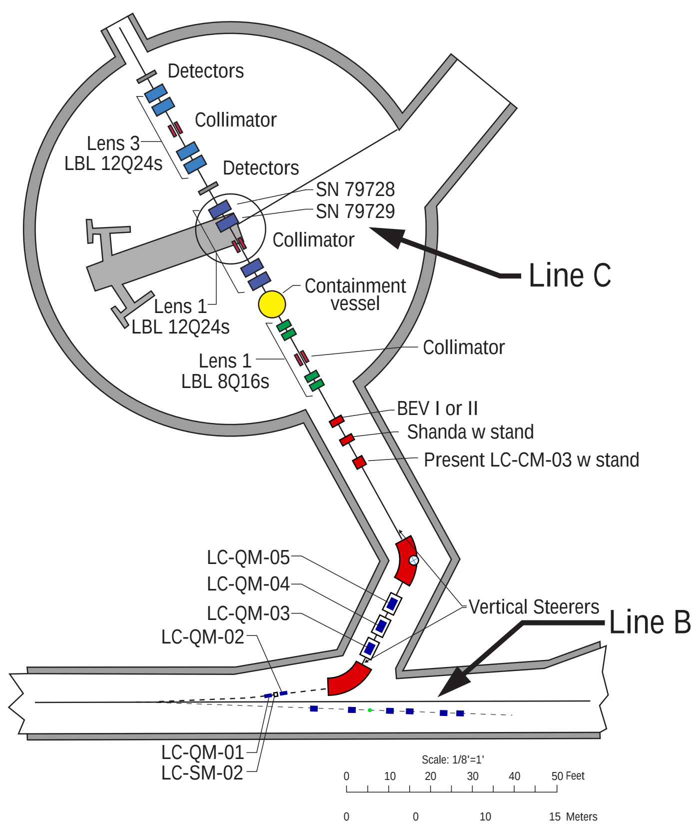
***Fig. 1** Artist's concept of the proposed 12-axis AHF.*

explosives. The principal tool of hydrotesting is thick-object-penetrating radiography. The images obtained must be formed very quickly (in ~50 ns or less) to freeze the motion of the moving components and features and to avoid motion blur. The images are negatives, in that the information depicting the primary assembly's internal structure is obtained from the attenuation of the penetrating radiation.

Such radiographs were traditionally created using x-rays, but recent experiments have demonstrated that proton radiography is a more robust solution. In proton radiography, a high-energy beam of protons impinges directly on the object to be radiographed. Unlike x-rays, protons undergo a large number of very forward-angle scatterings as they pass through the object and the exit window of the containment vessel. This introduces a blur to the image that is then removed, for the most part, by a magnetic lens system between the object and the detectors. The residual blurring can be further reduced by increasing the energy of the proton beam. For typical weapon-primary assemblies and containment-window thicknesses, submillimeter resolutions can be obtained with proton beam energies near 50 GeV, which can be produced in conventional accelerator architectures.

Protons have a number of advantages over x-rays in producing radiographic images. Protons have long, mean-free paths that are well matched for imaging thick, dense objects, and the proton results are sensitive to both material density and composition. The final images produced with protons also have a significantly higher

Fig. 2 Proton radiographic facilities on Lines B and C at LANSCE.



signal-to-noise ratio than x-ray images. In addition, protons provide a high detection efficiency that can generate many frames and simultaneous view directions of the explosion, producing a kind of "motion picture." Proton radiography is also easier to execute. There is no need for a bremsstrahlung converter (which is needed to produce x-rays by converting high-intensity electron beams) because the proton beam directly illuminates the object. Furthermore, proton accelerator technology already exists to provide the required beam energies, intensities, and time structures, making this technique a viable alternative for immediate application.

Proton Radiography at LANSCE

Our experiments at LANSCE addressed specific problems involving detonation-wave propagation inside a high-explosive assembly as a function of temperature and other high-explosive properties. LANSCE is capable of providing 800-MeV protons, which are well-suited for examining shock-wave propagation in small-scale, high-explosive systems. This lower energy limits the sample candidates to relatively thin, low-Z systems. These limitations arise primarily from multiple scattering and energy loss within the object and aberrations in the lens system—effects that become less important as the beam energy increases.

In preparation for our experiments, we installed new beam line diagnostics, a containment vessel, and a lens system in LANSCE's Line B area. Figure 2 shows a schematic of the Line B area used for the FY97 shots. Figure 2 also shows a schematic of a facility upgrade recently commissioned in Line C. The new Line C facility has a three-lens system, permitting beam, density, and material identification measurements. It is also capable of handling larger explosive charges because it can accommodate a larger containment vessel.

We conducted 25 dynamic shots on Line B from April to August 1997 to investigate the characteristics of shock propagation in different lots of high explosives over a range of temperatures. Typically, four to six frames were taken of each explosion. Figure 3 shows a detonation wave at four different times in a high-explosive assembly. The detonation wave is clearly evident in the radiographs as it propagates from the detonator to the outer surface of the explosive materials. The images were recorded on a phosphor image plate that allows one image per shot. An active camera system has now been installed and used to capture up to 12 frames in the time of a single high-explosive detonation. Future detector development is expected to provide the ability to take thousands of frames during the explosion to produce a more detailed motion picture of the event.

Many modern nuclear weapons incorporate insensitive high explosives (IHEs) to greatly reduce the chance of an accidental detonation during transportation or handling. Because of the reduced sensitivity of the IHE, its initiation and detonation is much more difficult to accurately model in computer codes, making

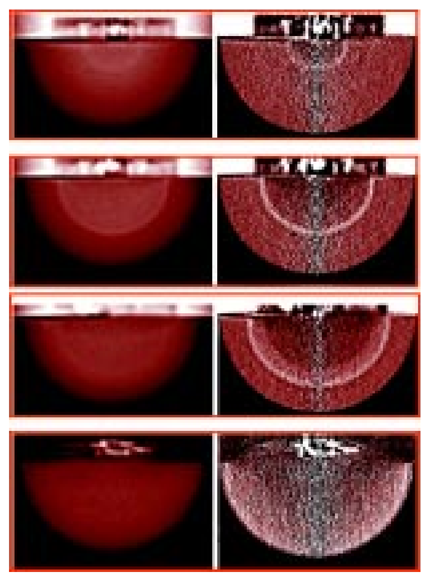


***Fig. 3** Analysis results from proton radiographs of the detonation wave in a high-explosive assembly at four different times. Areal densities (left) and reconstructed volume densities (right), extracted under the assumption of axial symmetry, are shown.*

reliable weapons detonation more difficult to guarantee under a wide range of conditions. The LANSCE proton radiographs provided an extensive set of data for IHE detonation for various initial conditions and temperatures. Such data show that our present calculational models have shortcomings and will help us develop and validate better models. This better understanding will help us maintain our confidence in these weapons into the future.

The dynamic experimental program at LANSCE has been an unqualified success, demonstrating our ability to perform dynamic experiments at high resolution, incorporate a containment system, eliminate blur with magnetic lenses, extract material composition using multiple lens techniques, and utilize the multiple pulse capability of the accelerator with a multiframing detection system. Upcoming experiments will include extensions of the IHE studies and high-explosives experiments in collaboration with the Atomic Weapons Establishment, Livermore, and Sandia National Laboratory.

High-Energy Proton Radiography at the AGS

In addition to our work at LANSCE, we are preparing to conduct static demonstrations using high-energy protons (up to 25 GeV) at Brookhaven's AGS. This is a major milestone because it demonstrates performance at parameters near those proposed for the AHF.

In preparation for the 25-GeV experiments, we collected data using a secondary beam from the AGS that provided only 7–10 GeV protons at low intensity. The lower intensity prevented us from performing true flash radiography, but the resulting data were able to demonstrate the low background level at the detector, confirm calculations of system performance, and prove the utility of the magnetic lens system at high energies.

To achieve a true flash radiograph of a static object, we have begun construction of a new beam line at the AGS to deliver the full energy of the accelerator (25 GeV) at full AHF intensities (10^{11} protons per pulse). We are installing two sets of lenses to allow for determination of material composition as well. The goal of the experiment is to demonstrate a few percent density measurement on a 1-mm^2 pixel size for thick objects (several hundred grams/cm^3) in the presence of a containment system. A suite of classified and unclassified static objects will be radiographed as part of this program. In addition, we will characterize the experimental backgrounds seen by the detection system. Other information on tomographic reconstruction, detector performance, and novel lens concepts will be gathered if time permits. We expect to complete the new AGS beam line and conduct a two week run in August 1999. The need for further runs will be evaluated based on the results of the August run.

Plans for a Proton Radiography Interim-Step Machine

We are currently assessing the feasibility of building a machine dedicated to testing proton radiography that would serve as an intermediate step to the AHF. Researchers from Los Alamos and Livermore have developed a concept for constructing a one- to two-axis, high-energy (25–50 GeV) ring using existing magnets from a decommissioned accelerator at Fermi National Laboratory. This proton radiography interim-step machine (PRISM) is estimated to cost approximately 10–20% of the proposed AHF and would provide a valuable testing ground to perform contained hydrotests with protons. Although limited by a minimal number of viewing axes (upgradable in the future), it would be capable of achieving full AHF resolutions, have the ability to perform material identification through a multiple lens system, and deliver the stored pulses (~20) over a long time-window using an extraction kicker system. This would provide both a technology development capability, as well as a unique tool for providing data to the SBSS program. PRISM could be constructed at either the Nevada Test Site or at Los Alamos. Advantages of a Los Alamos siting include use of LANSCE as an injector to the main ring to reduce cost, extensive accelerator infrastructure and expertise, and the existence of a vigorous hydrotesting program. Nevada Test Site offers an existing firing site. We are currently working with Livermore to evaluate these options, and we will submit a preconceptual design report within the year. An artist's concept of PRISM is shown in Fig. 4. PRISM would be a first step toward the AHF, and would include the linac (or comparable) injector, the main 50-GeV acceleration ring, a one- to two-axis extracted beam line, a firing point, and a lens/detector system.

Fig. 4 Artist's concept of PRISM.